GL-TR-89-0268

AD-A224 395

The Temple 2 Dust Trail

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28 September 1989

Scientific Report No. 2

GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; Distribution Unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
GL-TR-89-0268

6a. NAME OF PERFORMING ORGANIZATION
Steward Observatory

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
Geophysics Laboratory

6c. ADDRESS *(City, State, and ZIP Code)*
University of Arizona
Tucson AZ 85721

7b. ADDRESS *(City, State, and ZIP Code)*
Hanscom AFB, MA 01731-5000

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F19628-87-K-0045

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
63220C	S321	10	AA

11. TITLE *(Include Security Classification)*
(U) The Tempel 2 Dust Trail

12. PERSONAL AUTHOR(S)
Sykes, M.V., R.G. Walker, and D.J. Lien

13a. TYPE OF REPORT
Scientific #2

13b. TIME COVERED
FROM ________ TO ________

14. DATE OF REPORT *(Year, Month, Day)*
1989 September 28

15. PAGE COUNT
24

16. SUPPLEMENTARY NOTATION
Submitted to ICARUS

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
03	01	
03	02	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Infrared
Solar System
Interplanetary Dust
Comets

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The Tempel 2 Dust Trail was extensively observed by the Infrared Astronomical Satellite. Evidence is presented suggesting that the trail is composed of particles on the order of 1 mm and larger in diameter with velocities of several meters per second relative to the parent comet, assuming isotropic emission. Trail particles forward of the comets orbital position have a minimum diameter of ≈6 mm. These particles were emitted by the nucleus over a few hundred years. Excess color temperatures relative to a blackbody indicate that the particles either are large enough to support a temperature gradient over their surfaces or that a small particle population exists with diameters < 100Å. In the case of the latter, such small particles would have to have originated from the large particles, otherwise their acceleration by the gas outflow to km/s velocities would have prevented their ejection into trail orbits. Keywords:

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

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22c. OFFICE SYMBOL
AFGL/OPC

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

Introduction

Observations of cometary dust at visual wavelengths are dominated by particles microns in size. At thermal wavelengths emissions from submillimeter and larger particles become important. Dust trails are phenomena which were first detected by the Infrared Astronomical Satellite (IRAS), and have been identified as large debris covering portions of the orbits of short-period comets. (Sykes *et al.*1986a). Their name derives from their narrow and extended appearance in the infrared sky, some covering many tens of degrees - much like airplane contrails. At the time of the IRAS mission, the Tempel 2 dust trail (Fig. 1) was by far the most prominent such structure, rivaling the zodiacal dust bands in brightness, and covering a large fraction of the ecliptic longitudes scanned by the satellite. It was first detected as a string of 25 μm sources seeming related to periodic comet Tempel 2 (Davies *et al.*1984). Subsequent analysis of these detections indicated that they may be low-velocity emissions of submillimeter radius particles (Eaton *et al.*1984).

The present work was instigated by recent capabilities to better identify dust trail material over a larger fraction of a comet's orbit, and begin the systematic extraction of dust trail fluxes from the IRAS database. Because it is the brightest and most extensively observed trail, our initial efforts focus on the Tempel 2 dust trail as a paradigm for the phenomenon.

Observations

IRAS was launched into a nearly polar orbit in January of 1983, at which time it began scanning the sky in circles of constant solar elongation. The orbit precessed by $\sim 1°$/day to maintain the satellite's position above the terminator on the earth. The IRAS detector array swept out a path on the sky $0\overset{\circ}{.}5$ on the sky and the solar elongation was shifted so that on subsequent orbits the scans would overlap by $0\overset{\circ}{.}25$. Sources would thus be detected twice on timescales of an hour, a proceedure referred to as "hours-confirmation" or HCON. Maintaining solar elongation angles between 80 and 100 degrees, a section of sky would be mapped over the course of a week (HCON 1), and would then be repeated (HCON 2). In this fashion the entire sky was observed 4 times after 7 months. The sky referred to here, however, is the sky at infinity. This meant that a section of the solar system was missed entirely. Figure 2a and b shows the coverage of the Tempel 2 orbit over this period.

In the last 3 months of the mission, 72% of the sky was surveyed a third time (HCON 3), before the helium cryogen was lost and the detectors ceased functioning. This last survey covered much of the solar system beyond the earth's orbit which had been missed earlier (Fig. 2c). So over the entire mission, all mean anomalies of the Tempel 2 orbit were scanned. However, since material in the orbit is in motion about the sun, it is also important to understand the coverage of the orbit in a dynamical reference frame. Figure 3 shows the coverage of the orbit relative to the location of the comet as a function of time. In this dynamical frame we see that all parts of the orbit relative to the comet are

scanned, but, more importantly, that almost half of all the scans crossed the orbit less than 20° behind the comet's position in mean anomaly. This repeated scanning of the same orbital segments were due to the compensating motions of P/Tempel 2 and the Earth. As the IRAS orbit precessed to compensate for the Earth's angular motion about the sun, the comet (and material in its orbit) would similalry shift in position and be scanned again. Since dust trails are brightest nearest and behind the parent comet, this explains, in part, the prominence of the Tempel 2 trail.

In addition to the favorable viewing geometry, the brighter portions of the trail being repeatedly scanned were observed as they passed through both perihelion and perigee (Fig. 4). During perihelion passage, the surface brightness of the trail is maximum at thermal wavelengths, and its proximity to the earth resulted in parallactic spreading of the trail position over a large range of geocentric ecliptic longitudes (Fig. 5).

Dust in the orbit of Tempel 2, however, is not restricted to the vicinity of the comet nucleus. To date, we have detected emission from $2\overset{\circ}{.}3$ ahead to 60° behind the comet in mean anomaly (Fig. 6). Dust may extend completely around the orbit, but the surface brightness of the trail is found to monotonically decrease in brightness away from the comet.

The following data presented in this paper are extractions from the IRAS Calibrated Reconstructed Detector Data (CRDD), in which individual detector data streams from individual satellite scans have been phased and coadded in order to maximize the signal-to-noise ratio, and then deconvolved from the IRAS in-scan beam profile to resolve the true debris trail profile. Details of the IRAS focal plane detector array and a description of the CRDD may be found in the IRAS Explanatory Supplement (1988).

Individual scans of the trail by IRAS are used to determine trail surface brightness (Fig. 7) and width (Fig. 8) by fitting a gaussian of the form $\exp[-\pi(x/\sigma)^2]$ to the deconvolved trail profile. Since we know the geocentric and heliocentric distance of the trail segment scanned, we can determine the equivalent width of the trail in kilometers, the thermal characteristics of the trail particles, and estimate the spatial density and mass of the material observed.

Particle Sizes and Velocities

The relationship between trail width, D, and the velocities of the trail particles relative to the comet, Δv, can be estimated (following Sykes *et al.*1986b) by assuming that the earth lies in the comet orbit plane and that the width of the trail at a given location represents the maximum excursion of trail particles from the comet orbital plane. These are reasonable assumptions in our investigation of the Tempel 2 dust trail because of the relatively low inclination of the comet ($12\overset{\circ}{.}4$ - typical of short-period comets) and the fact that the trail width does not appear to vary over its observed length within the resolution of the IRAS skyflux maps ($\sim 4'$) (IRAS Expl. Supp. 1988). Thus,

$$\Delta v \approx \frac{v}{2}\frac{D}{R_\odot} \qquad 1$$

where v is the orbital velocity of the comet at the time of emission and $R_\odot$ is the heliocentric distance of the trail.

At the higher resolution of individual CRDD scans ($< 0.5'$) the width of the trail is resolved. These scans show an increase in width within 3° mean anomaly of the comet (Fig. 8), which may correspond to the most recent trail particle emissions filling the envelope defined by the small inclinations of their new orbits relative to orbital plane of the parent comet. Using the maximum trail widths from the CRDD scans, the velocity of the Tempel 2 dust trail particles relative to the comet is 3.5 m/s, assuming emission at perihelion. For emissions near aphelion this would correspond to relative velocities near 1 m/s. Such low values imply that trail emissions detected furthest from the comet may have occurred several hundred years ago.

As a consequence of their low relative velocities, trail particles are distributed along the comet's orbital path. Radiation pressure induces a splitting of the trail particle population. Particles below a critical size are only found behind the comet in its orbit while particles larger than this size are found both ahead and behind the comet (Sykes *et al.*1986b). Basically, when a particle escapes from the comet, it finds itself in an independent heliocentric orbit about a sun effectively less massive (as a consequence of radiation pressure) than that experienced by the comet. The semi-major axis of this orbit (assuming an initial instantaneous velocity equal to that of the comet) is somewhat larger and its mean orbital velocity somewhat lower than that of the parent comet. The particle falls increasingly behind the comet's orbital position. If the particle escapes the comet with some small velocity, but random direction, it could be injected into an orbit having either a higher or lower semi-major axis than the comet (assuming no radiation pressure). The critical particle size is that in which the mean motion effects of radiation pressure and relative velocity cancel:

$$\left[\frac{GM_\odot(1-\beta)}{(a_o+\Delta a_{ej}+\Delta a_{rp})^3}\right]^{\frac{1}{2}} - \left[\frac{GM_\odot}{a_o^3}\right]^{\frac{1}{2}} = 0 \qquad (2)$$

where G is the gravitational constant, $M_\odot$ is the mass of the sun, a_o is the semimajor axis of the comet's orbit, Δa_{ej} and Δa_{rp} are the differences in semimajor axes due to the difference in particle and comet orbital speeds (Δv) and radiation pressure, respectively. For perihelion emissions, to first order in Δv and β,

$$\Delta a_{ej} = 2a_o\left(\frac{\Delta v}{v}\right)\left(\frac{1+e_o}{1-e_o}\right) \qquad (3)$$

$$\Delta a_{rp} = a_o\beta\left(\frac{1+e_o}{1-e_o}\right) \qquad (4)$$

The eccentricity of the comet orbit is e_o, and β is the ratio of the radiation force to gravitational force acting on a particle. It is related to a spherical particle with diameter (d) through the relation (Burns *et al.*1979)

$$\beta = \frac{1.14 \times 10^{-4}}{\rho d} Q_{\rm pr} \tag{5}$$

where ρ is the particle mass density (assumed to be 1 g/cm^3), and $Q_{\rm pr}$ is the radiation pressure efficiency factor (assumed to be unity). For aphelion emission the sign of e_o in (3) and (4) is reversed. In the case of Tempel 2, the range of minimum β's for the forward trail corresponds to particle diameters of 5.5 mm to 7.4 mm for perihelion and aphelion emissions, respectively.

A lower limit of trail particle sizes *behind* the comet's orbital position is obtained by comparing the trail position with zero-velocity syndynes calculated for the epoch of observation. Observations of the P/Tempel 2 and its trail are used which were taken by IRAS on September 6, 1983 and are shown in Fig. 9. Overlaying the image constructed from IRAS scans is a map of syndynes for β's ranging from 0.01 to 0.0005. The syndynes are for zero velocity emissions. Non-zero velocity isotropic emmissions result in a "fan" centered about the zero-velocity syndyne, while non-isotropic emission can shift a similar fan up or down relative to the zero-velocity syndyne. Since we are not attempting to uniquely constrain any anisotropy in the dust emission from the comet (and since such anisotropy would have to reproduce over many orbits), the overlay provides reasonable first-order constraints on trail β's.

The maximum trail β is $\leq 10^{-3}$, which corresponds to particle diameters ≥ 1 mm. Particles having β's smaller than this converge onto the trail. The "split" between the comet tail and trail corresponds to a location in which only a narrow range of β's are expected to be found. Trail modelling has not yet reached the stage at which we can say whether dust trails represent an enhancement of large particles over that expected from particle size distributions for large particles (e.g. Sekanina 1979).

Thermal Properties

When ejected from the comet nucleus, Tempel 2 trail particles may possess significant ice components. Since these particles come as close as 1.4 AU from the sun, such ices are very unstable and would sublimate on short timescales (e.g. Lien 1989). Trail particles thus represent the refractory component of the comet nucleus material. Earlier work indicated that the Tempel 2 dust trail material is very dark (Sykes 1988), having an albedo comparable to that measured for the surface of comet Halley (Keller *et al.*1986; Sagdeev *et al.*1986), however there were large uncertainties in this value as a consequence of using data from IRAS skyfux maps in which the trail width was not resolved. Temperatures have since been measured for individual scans of the trail at different heliocentric distances (Fig. 10) and show that they are consistently warmer than that expected for a

rapidly rotating blackbody at the same heliocentric distance. Three possible hypotheses explaining this observation include the existence of a small particle component of the dust trail, large rough particles, and particles large enough to maintain a temperature gradient across their surfaces.

When excess temperatures are observed in the comae of comets, it is generally ascribed to the presence of small particles which radiate inefficiently at thermal wavelengths (e.g. Ney 1982). Silicate emission features may also be observed. Though decreasing the radius of a particle tends to increase its sensitivity to radiation pressure (β), this trend is seen to reverse for several different compositions at $\sim 0.1\mu$m (Burns *et al.*1979). The existence of very small low-β dust particles in the Tempel 2 trail would automatically discriminate among possible minerologies of the small particle population.

There is an initial problem with applying the small particle hypothesis to trail particles: sub-micron particles will be accelerated to velocities of ~ 1 km/s by the comet gas outflow and will not be injected into trail orbits. This is true, however, only if such particles originate from the comet surface. There are two mechanisms by which this problem might be avoided:

(1) Trail particles may be very porous, and initially filled with interstitial ices in which the small particles are imbedded. The trail particles continue to outgas after having travelled far enough away that small low-β particles would not be coupled to the comet gas outflow and would behave dynamically like the large trail particles.

(2) Mechanical stresses on trail particles during devolitilization results in small particles fragmenting off.

This hypothesis may be tested by looking for a silicate emission feature in thermal spectra of the trail, utilizing the IRAS Low-Resolution Spectrometer data - an effort currently underway (Lynch, private communication).

Another test would be to look for a decrease in the excess color temperature as a function of distance from the comet. This might come about due to the removal of small particles from the trail with time by mechanisms such as sputtering and electrostatic charging through photoionization (and removal by Lorenz forces). Even if we are looking at emissions from over a period of a few hundred years, however, the potentially large timescales of such processes (e.g. Drain and Salpeter 1979) may preclude the observation of such an effect.

Large rough-surfaced particles have been shown in numerical simulations to exhibit excess color temperatures relative to that expected for spherical grains (Lamy and Perrin 1988). The magnitude of the effect for astronomical silicates comparable in size to the trail particles is less than 1% - much smaller than that seen here. However, such modelling has yet to be extended to other compositions.

If the particles are large enough, they may support a temperature gradient across the surface, effectively behaving more like asteroids than isothermal grains. This may be described by two models: (1) a "slow rotator" model in which the surface is in instantaneous radiative equilibrium with the insolation, and (2) a "fast-rotator" model in which

the surface at a given angle from the spin axis is in radiative equilibrium with the *average* received insolation. In both cases, local equilibrium temperatures will exceed isothermal blackbody temperatures near the subsolar point or latitude, respectively, while being cooler on the "night" side or near the rotational poles.

As we increase our observational phase, more of the cooler "dark" sides of the above models will be observed. The result is a decrease in the ratio of observed color temperatures to blackbody temperatures with increasing phase. IRAS observed the Tempel 2 trail over 25° of phase. Unfortunately, the data obtained for the present work were extracted from scans made within a single narrow range of phases.

Mass loss

If the trail particles have a steep power-law size distribution similar to that given by Sekanina (1979) for large particles, then most of the mass as well as surface area will be in the smallest particles ($d \sim 1$ mm). Further assuming a trail depth along the line of sight equal to the apparent width of the trail normal to that, the number density of trail particles measured nearest to the comet is $\sim 3 \times 10^{-16}/\text{cm}^3$, Or one particle in a box 1.4 kilometers on a side. An estimate of the upper limit to the observed trail's mass is thus 3×10^{14} g, equivalent to a sphere 0.8 km in diameter. Comparing this with the 10.4 km effective diameter of the Tempel 2 nucleus at maximum light (A'Hearn *et al.*1989), we conclude that the trail represents only a small fraction of total mass that should be lost over a couple hundred year period if the comet loses all of its mass in 10,000 orbits.

While the dust trail may not represent a significant loss of mass for Tempel 2, the collection of such debris along its orbit could potentially be a significant spacecraft hazard. In the worst case scenario of the above maximum number density of particles, a vehicle such as the Comet Rendesvous/ Asteroid Flyby (CRAF) spacecraft, with an estimated impact parameter of 10 m^2, would only have to travel 330,000 km (less than 8 trail widths) before having a 1 in 3 chance of impacting a millimeter-sized particle.

Discussion

The particle diameters discussed in this paper are something of a fiction. The real parameter being constrained is β which is related to diameter through equation (5), assuming smooth spherical particles of known mass density and Mie scattering theory. Cometary particle densities may actually be much less than unity, based on analysis of upper atmosphere meteor tracks. This would greatly increase the inferred trail particle diameters, and have effects such as decreasing the number density of trail particles (making trails a less hazardous region for spacecraft operation) and increasing their coupling to the gas outflow from the comet (making greater relative velocities possible for larger particles). Lower densities are suggested when we compare particle sizes and velocities from this work with a detailed theoretical model of the Tempel 2 nucleus/coma interface developed by

Gombosi (1987) for CRAF. Assuming the same mass density for dust particles (1 g/cm^3), Gombosi calculates a dust velocity for several millimeter radius partices as being less than 1 m/s for perihelion emission. Lower mass densities would account for the somewhat larger relative velocities we determine.

Another issue is the relationship between dust trails and meteor streams. We know that meteor streams are associated with some comets, and it is reasonable to infer that what we observe as meteor streams began as dust trails. However, meteor streams are qualitatively very different from their trail counterparts in that they are far more dynamically evolved, are spread out over a vastly greater volume, and often have mean orbits whose nodes are significanlty separated from their parents. Estimates of meteor stream dimensions (Hadjuk 1989) and number densities (Koschack and Rendtel 1988, Rendtel 1989) indicates cross sectional diameters a thousand times that of the Tempel 2 trail and densities as much as nine orders of magnitude lower.

With the advent of spacebased infrared detectors such as IRAS it may be possible to trace some of the evolution of dust trails to meteor streams. There exists the possibility of detecting "orphan" trails detached from their present parent orbits (Sykes and Walker 1989), and perhaps the recently detected Type II dust trails (Sykes 1988) are a part of this transition.

Acknowledgments

This work was supported in part by the NASA Astrophysics Data Program and Air Force Geophysics Laboratory Contract No. F19628-87-K-0045.

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Figure Captions

Fig. 1. The ecliptic plane as seen by the Infrared Astronomical Satellite (IRAS) displaying the various components of extended thermal emission in the sky. The image is constructed from scans taken at 12, 60 and 100 microns. The broad diffuse emission is zodiacal dust, structures seen within this emission include the central asteroid dust bands (the narrow band crossing the image center), the Tempel 2 Dust Trail, and galactic cirrus. The image is centered on 1^h RA and 0° DEC, and covers 2 hours of RA (30°).

Fig. 2. IRAS coverage of the Tempel 2 orbit in each of the three HCONs. The orbit of Tempel 2 is projected onto the heliocentric rectangular XY-plane with the Earth's orbit drawn for reference. Individual scans are represented as dark lines.

Fig. 3. IRAS coverage, relative to the mean anomaly of Tempel 2, of the orbit over the course of the mission. Y-axis values are the mean anomaly of the comet minus the mean anomaly of the orbit segment observed. Positive values denote increasing distance in mean anomaly behind the comet. Two observations of the comet orbit were always made per satellite orbit.

Fig. 4. (a) IRAS coverage of the Tempel 2 orbit as a function of heliocentric distance and the angular distance (Δ Mean Anomaly) from the comet. The orbit was scanned by IRAS most often when the comet and the portion of the orbit between −10° and 40° away was near perihelion, at which time the trail material would be brightest at thermal wavelengths. (b) Coverage was also heaviest when the comet was near perigee.

Fig. 5. Material near the comet was observed over a very large range of geocentric ecliptic longitudes as a consequence of angular trail motion being comparable to the precession rate of the IRAS orbit, while the portion of the trail being repeated scanned neared perigee.

Fig. 6. The Tempel 2 dust trail as it would have appeared from above the solar system on June 1, 1983, the perihelion passage time of the comet. For reference, the earth's orbit is drawn as is the position of the earth. The directio of the 1st Point of Ares is shown to the upper right.

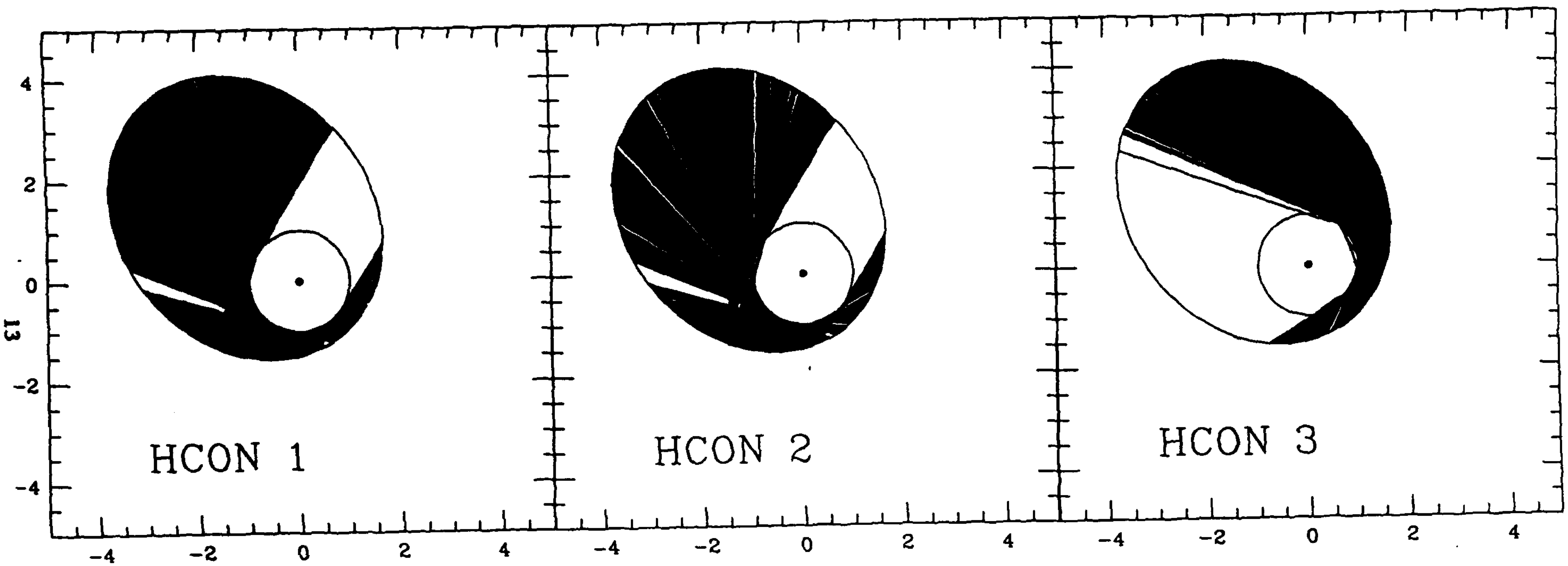
Fig. 7. Surface brightness densities of the Tempel 2 dust trail at the bandcenter wavelength of each of the IRAS passbands. They are 12 μm (circles), 25 μm (squares), and 60 μm (pentagons). Observations were made during July/August 1983 during HCON 1 (open circles) and HCON 2 (closed circles).

Fig. 8. The width of the trail corresponds to the equivalent width of the gaussian used to model the in-scan profile of the trail.

Fig. 9. IRAS sky survey scans have been regridded into two $1° \times 1°$ images to form this composite image of P/Tempel 2 and its trail on Sept. 6, 1983. The overlay shows the zero-velocity syndynes for particles having β's ranging from 0.01 to 0.0005 at intervals of 0.00025.

Fig. 10. Color temperatures for single-scan observations of the dust trail are determined by removing the zodiacal background utilizing a median filter, and fitting a blackbody curve to the integrated trail flux at 12, 25, and 60 μm using a least-squares method. The resultant temperatures have been binned in intervals of 0.01 AU.

FIGURE 1



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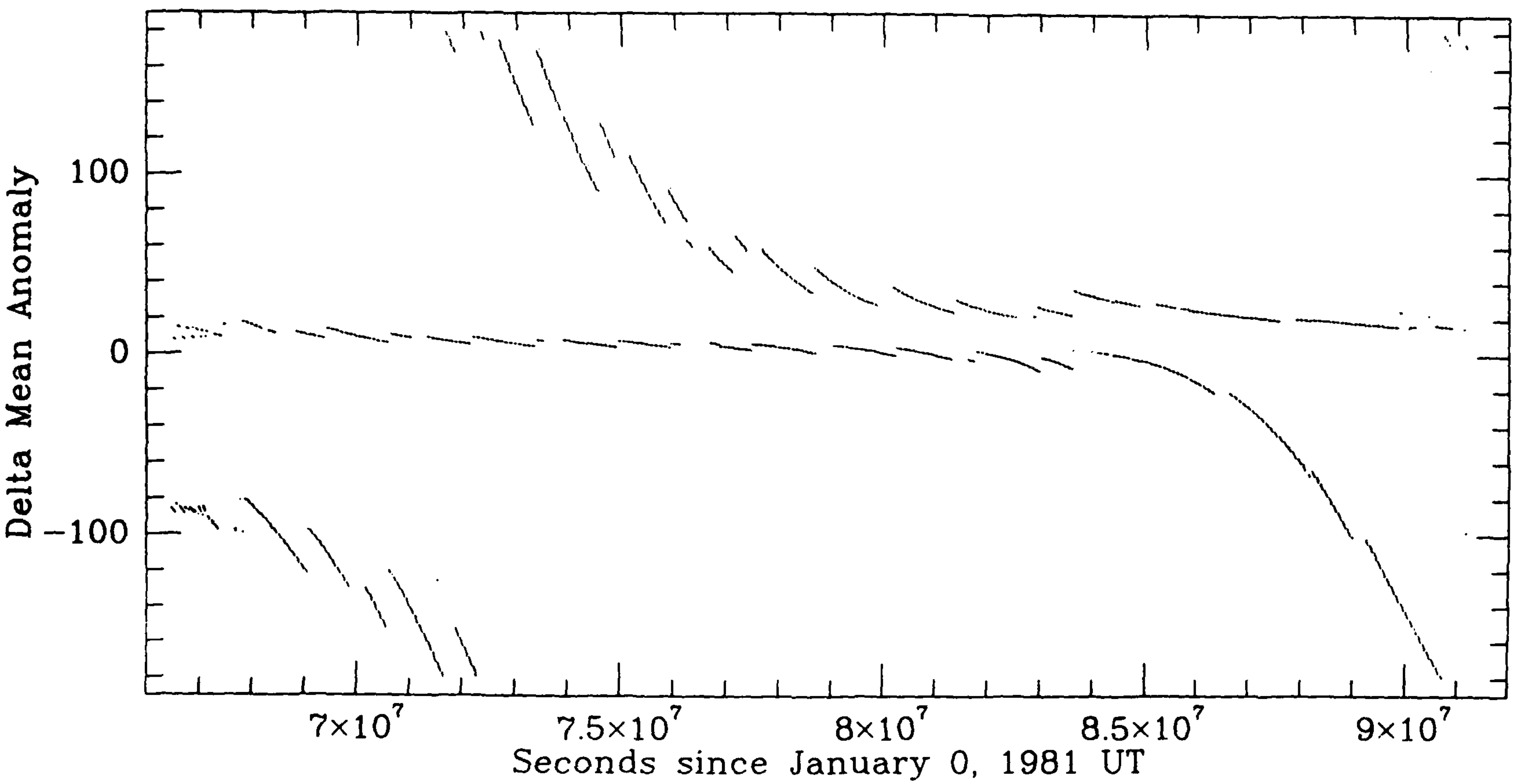
Delta Mean Anomaly
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−100
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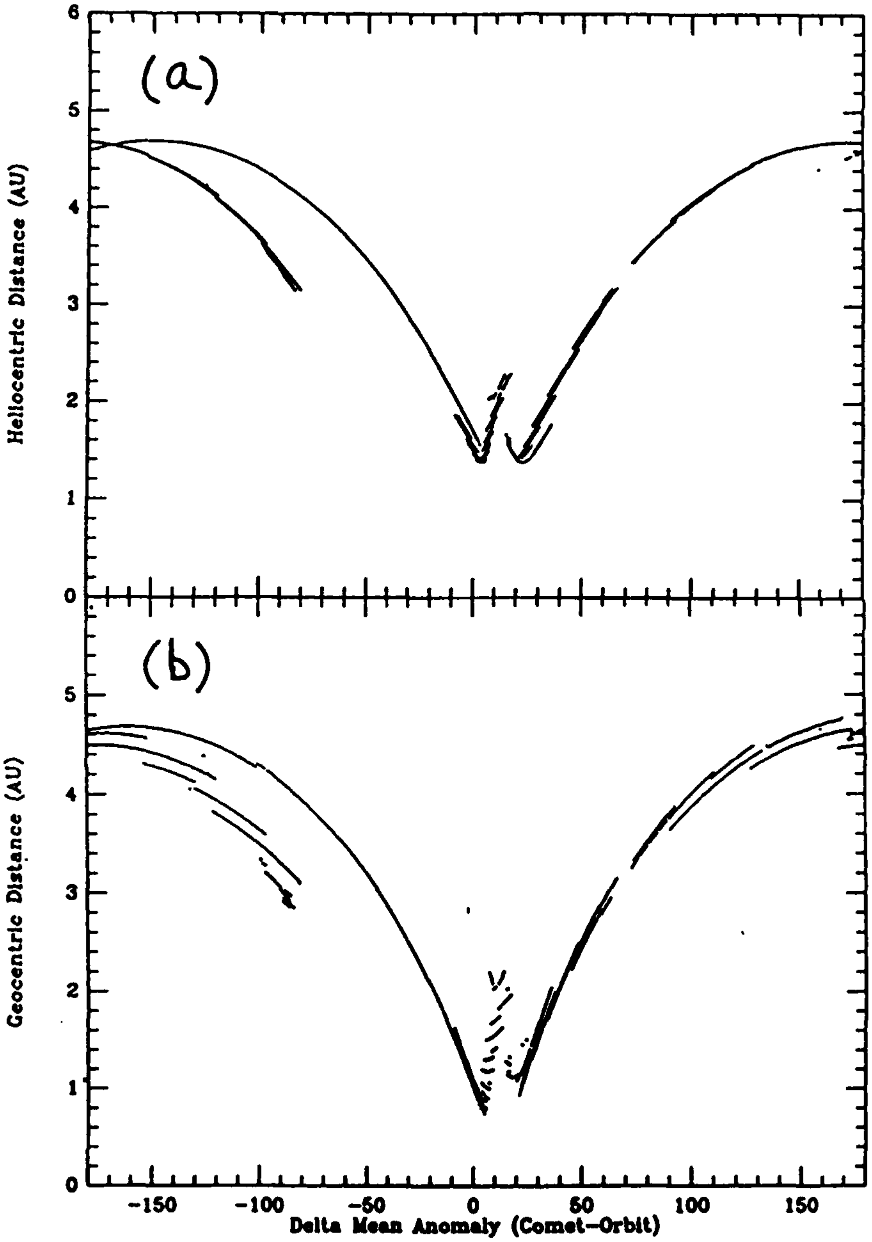
7.5×10^7
8×10^7
8.5×10^7
9×10^7
Seconds since January 0, 1981 UT

FIGURE 3



(a)
(b)
Heliocentric Distance (AU)
Geocentric Distance (AU)
Delta Mean Anomaly (Comet-Orbit)
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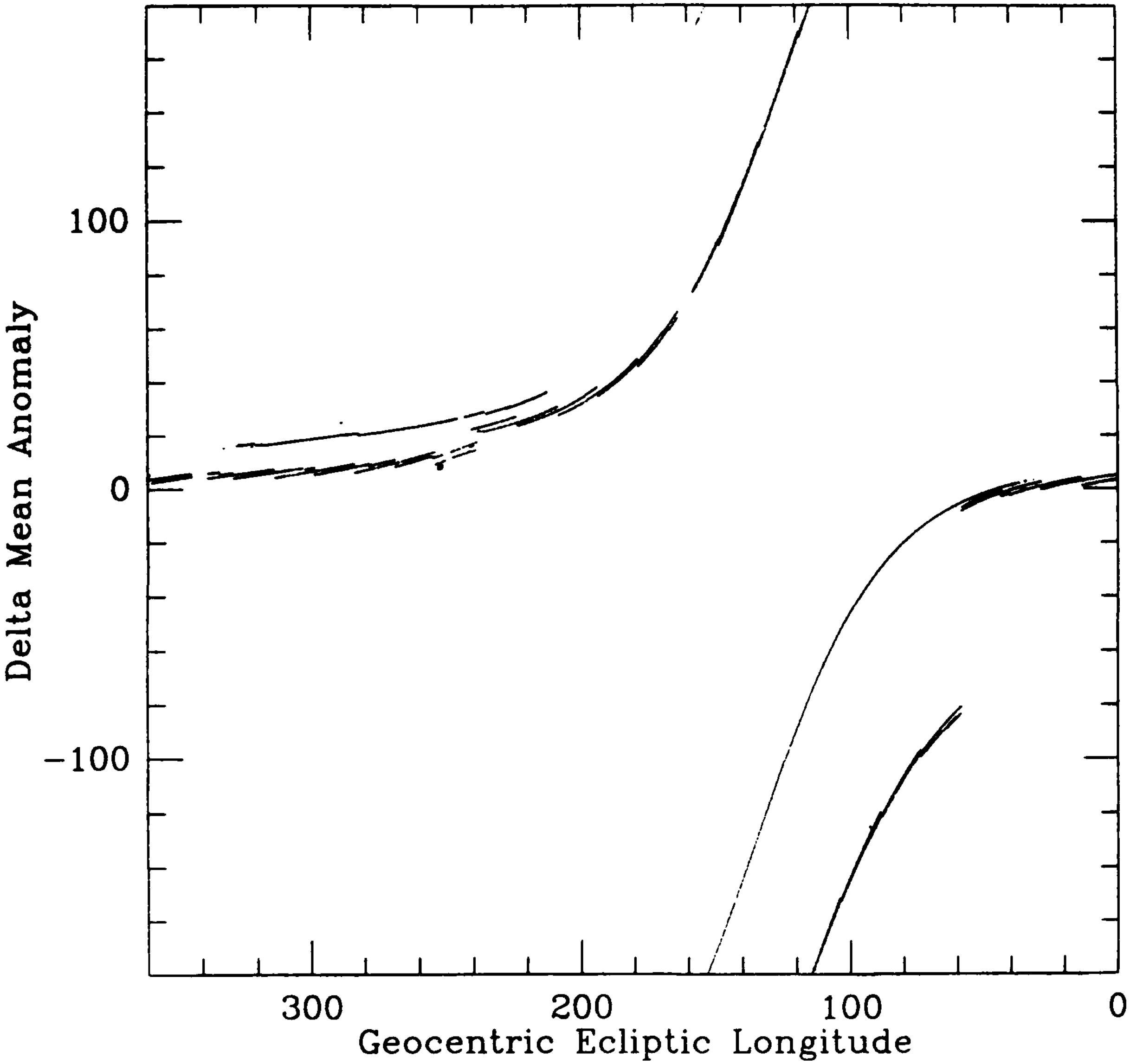
2
3
4
5
6
-150
-100
-50
0
50
100
150

FIGURE 4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200
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Geocentric Ecliptic Longitude

FIGURE 5

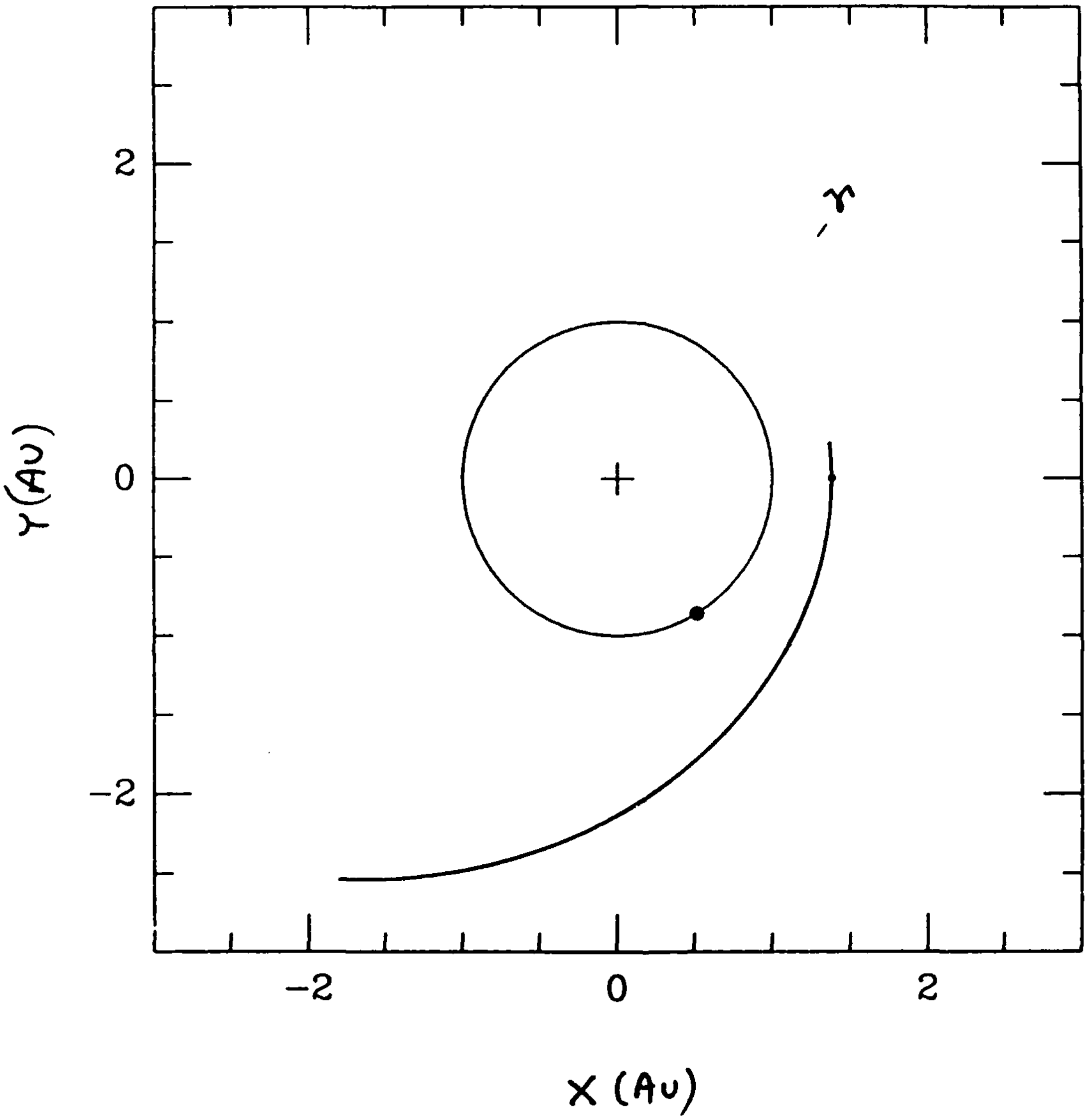
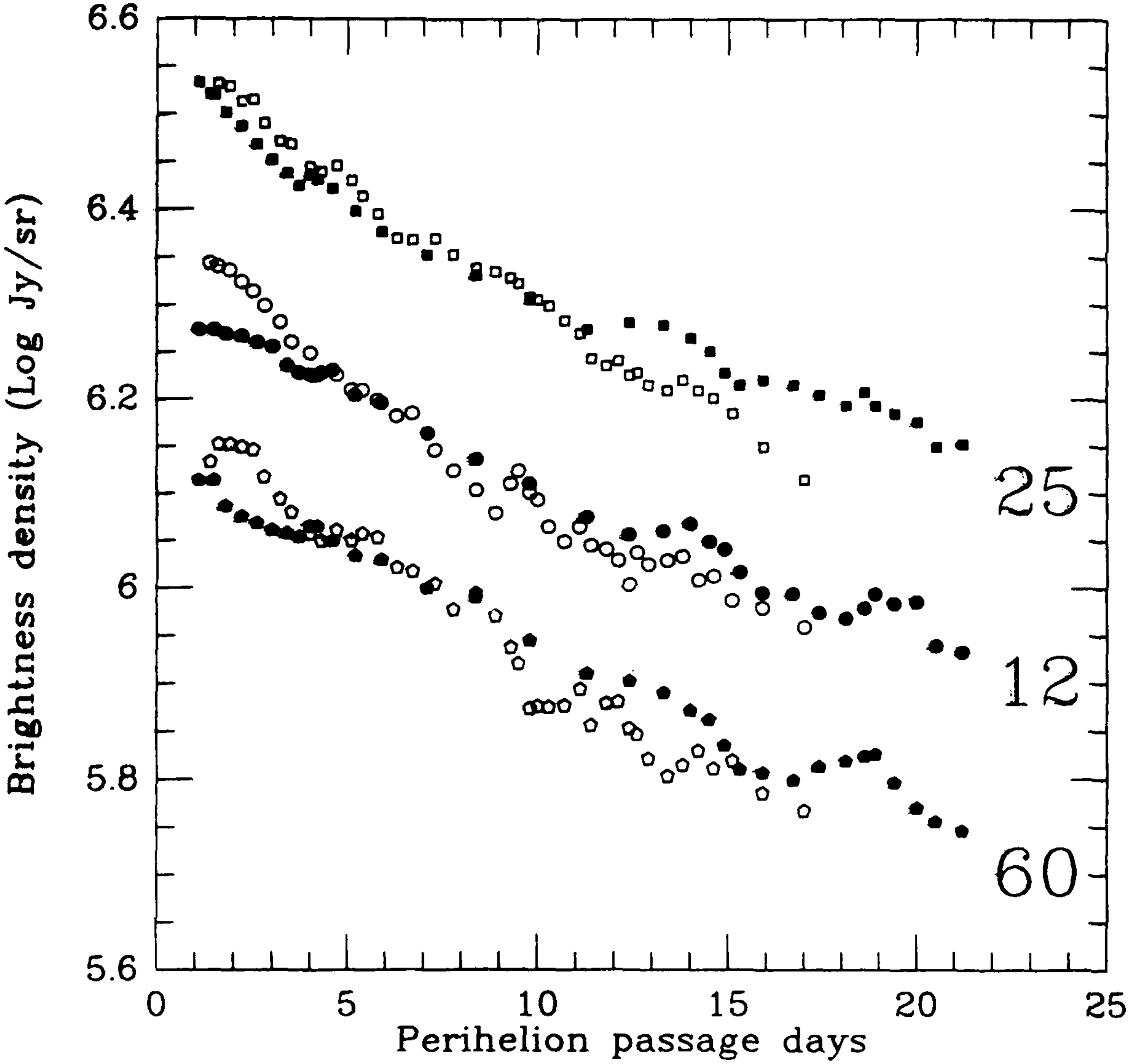


FIGURE 6



Brightness density (Log Jy/sr)
6.6
6.4
6.2
6
5.8
5.6
0
5
10
15
20
25
Perihelion passage days
25
12
60

FIGURE 7

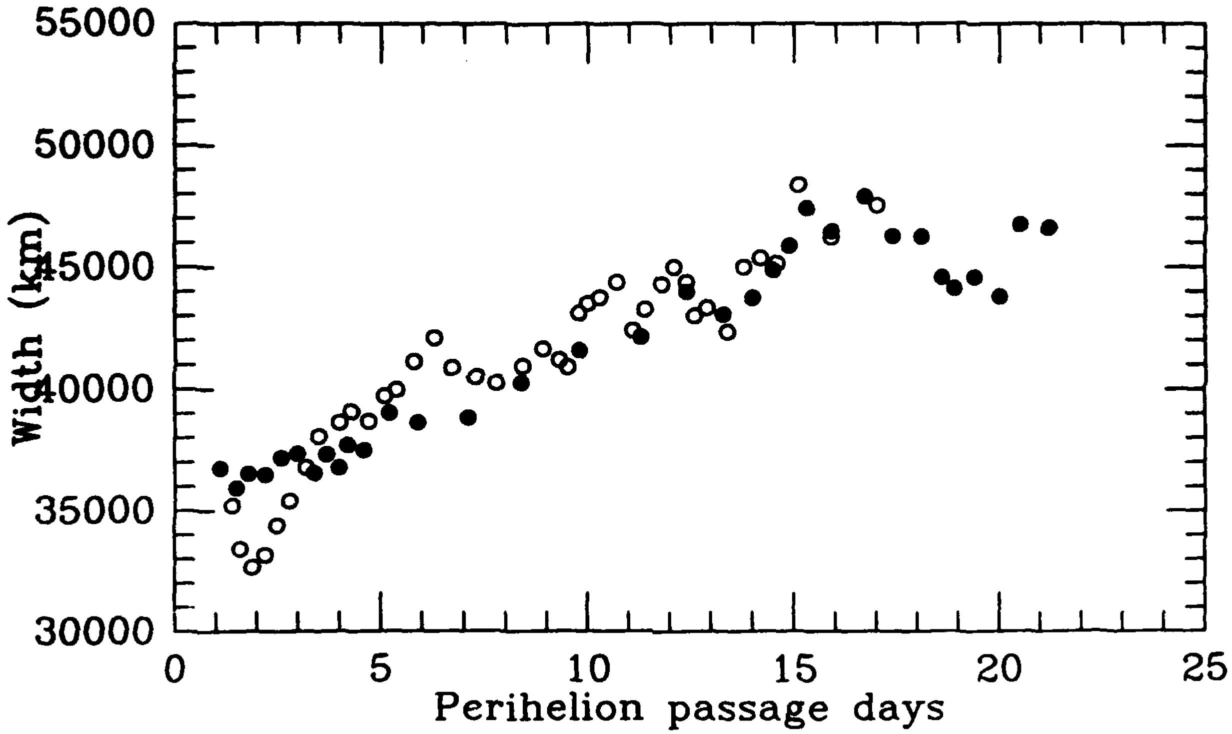

55000
50000
45000
40000
35000
30000
Width (km)
0
5
10
15
20
25
Perihelion passage days

FIGURE 8

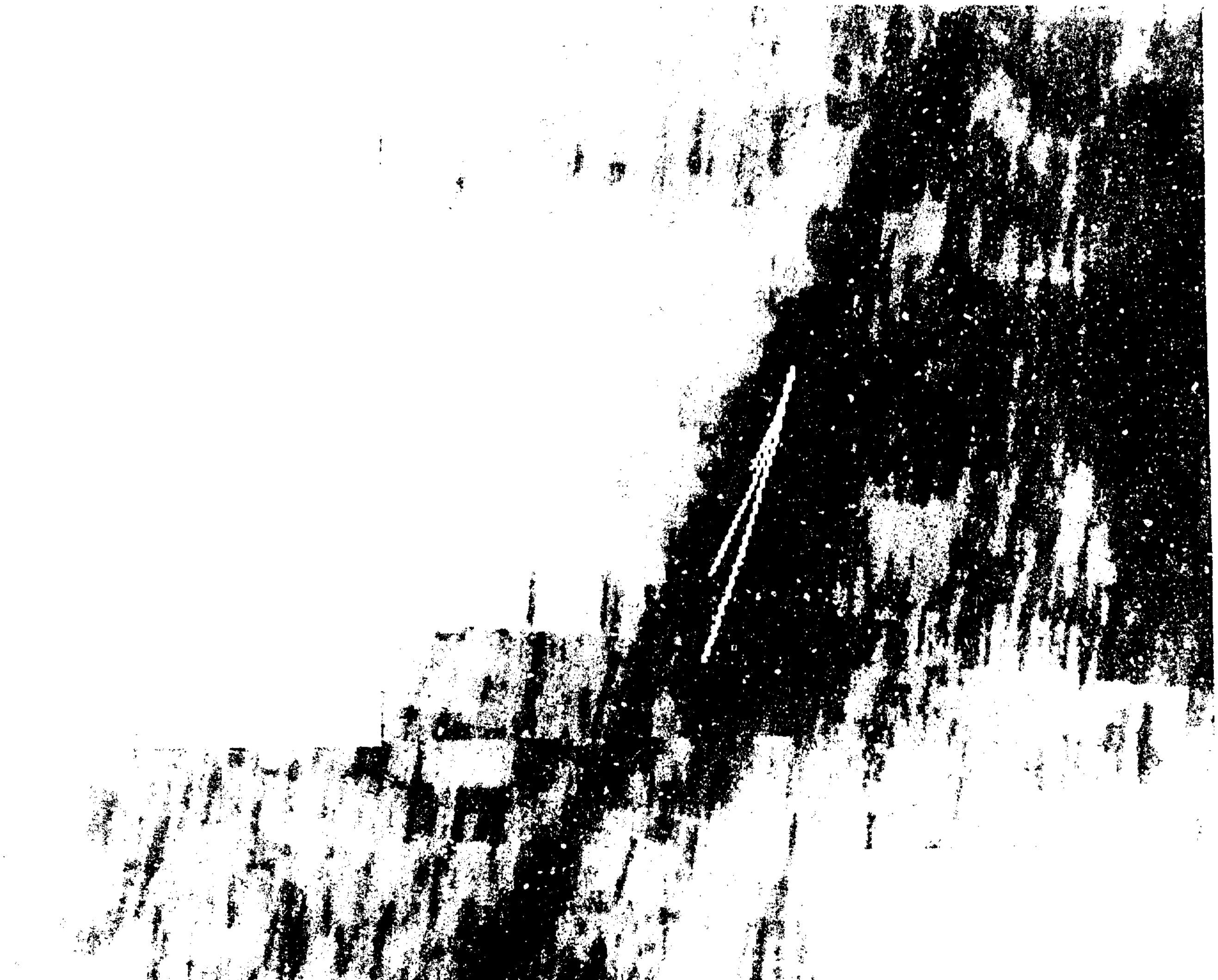


FIGURE 9

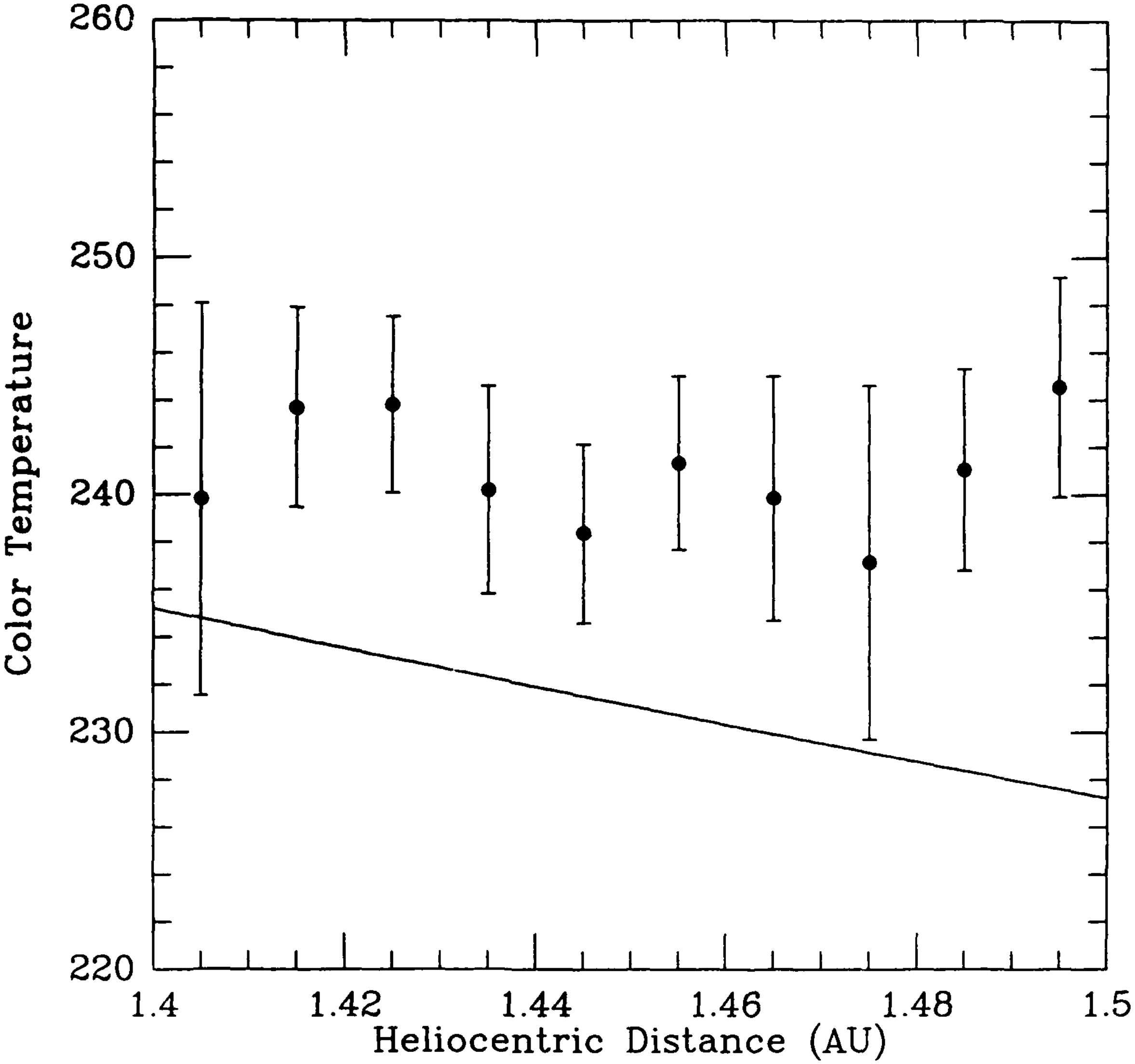

Color Temperature
260
250
240
230
220
1.4
1.42
1.44
1.46
1.48
1.5
Heliocentric Distance (AU)

FIGURE 10